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LITHIUM, BERYLLIUM, AND BORON IN THE PRIMARY COSMIC
RADIATION: OBSERVATIONS AT FORT CHURCHILL

by

G. D. Badhwar, S. N. Devanathan, and M. F. Kaplon

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The Energy Dependence of the Abundance of
Lithium, Beryllium, and Boron in the Primary Cosmic
Radiation: Observations at Fort Churchill*

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Abstract

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The relative abundance of Lithium, Beryllium, Boron, and the S-group nuclei has been determined at two different energies with the help of a pure nuclear emulsion stack flown from Fort Churchill, Canada ($\lambda = 70.5^\circ$) on 4 August, 1962 under a total of 4.7 g/cm^2 of residual atmosphere. The ratio of the L to S nuclei, L/S , at the top of the atmosphere between 200-700 Mev/n and $> 700 \text{ Mev/n}$ was determined as 0.41 ± 0.08 and 0.19 ± 0.03 respectively. The results of both the absolute flux values of L and S-group nuclei as well as their ratios are in accord with other investigations. Combined with the evidence from the measurements of ${}^3\text{He}$ in the same stack, our results indicate that low energy cosmic ray nuclei have traversed about twice as much hydrogen as high energy particles. The results rule out an accelerating mechanism of the Fermi type but may be explained by a source-trapping mechanism.

author

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1. Introduction

The universal abundance¹ of the L-group* nuclei is extremely

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1. (i) H. E. Suess and H. C. Urey, Handbuch der Physik 51
(ii) A. G. W. Cameron, Astrophys. J. 129, 676 (1959)
(iii) L. H. Aller, Handbuch der Physik 51
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small compared to that of the M and H-groups. Any significant amount of the L-group observed in the primary cosmic radiation

* The heavy nuclei in the primary cosmic radiation are grouped as follows: (i) the L-group consisting of Li, Be, and B nuclei ($3 \leq Z \leq 5$); (ii) the M-group consisting of C, N, O, and F nuclei ($6 \leq Z \leq 9$) and (iii) the H-group consisting of all nuclei with $Z \geq 10$. The group of nuclei with $Z \geq 6$ is called the S-group.

should therefore be the result of spallation reactions of M and H-group nuclei with interstellar matter. Consequently, $\frac{L}{S}$,⁺ the ratio of the number of L-group nuclei to the number of S-group nuclei should be capable of providing information on the amount of matter traversed by the galactic radiation before its arrival at the top of the earth's atmosphere. This ratio has been determined reliably² at a geomagnetic latitude of $\lambda = 41^\circ\text{N}$ (cut-off rigidity

2 F. W. O'Dell, M. M. Shapiro, and B. Stiller, J. Phys. Soc. (Japan) 17, Suppl A-III, 23 (1962)

≈ 4.5 GV). It has, however, been realized by various workers in the field, that a study of the variation of $\frac{L}{S}$, with rigidity or energy can, in principle, provide information on the amount of matter traversed as a function of rigidity or energy. This information is necessary for an understanding of the trapping mechanism proposed by Kaplon and Skadron³ for low energy (or rigidity)

3 M. F. Kaplon and G. Skadron, Nuovo Cimento, in print (1964)

particles. It has also been pointed out that a variation of the relative abundance of Lithium ; Beryllium : Boron, as a function of energy can yield information regarding the acceleration mechanism, ionization loss and estimates of gas density in interstellar space.⁴

4 G. D. Badhwar and R. R. Daniel, Prog. Theo. Phys. 29, 627 (1963)

It has been possible, in the recent past, to determine the isotopic

+ The ratio of the number of A-group nuclei to the number of B group/_{nuclei} is designated as AB.

composition of hydrogen^{5,6,7} and helium nuclei^{8,9,10,11,12,13}

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- 5 G. D. Badhwar, J. Geophys. Research, 69, Nov.1 (1964)
 - 6 M. V. K. Appa Rao and P. J. Lavakare, Nuovo Cimento 26, 740 (1962)
 - 7 S. N. Ganguli, N. Kameshwar Rao and M. S. Swami, Proc. Jaipur Conference (1963)
 - 8 M. V. K. Appa Rao, Phys. Rev. 123, 295 (1961)
 - 9 F. Foster and J. H. Mulvey, Nuovo Cimento 27, 93 (1962)
 - 10 B. Hilderbrand, F. W. O'Dell, M. M. Shapiro, R. Silberberg, and B. Stiller, Proc. Jaipur Conference (1963)
 - 11 H. Aizu, Proc. Jaipur Conference (1963)
 - 12 C. Dahanayake, M. F. Kaplon, and P. J. Lavakare, J. Geophys. Research, 69, 3681 (1964)
 - 13 V. K. Balasubrahmanyam, S. V. Damle, M. G. K. Menon, and S. K. Roy, Proc. Jaipur Conference (1963)
-

of the primary cosmic radiation. Supplemented by the determination of the ratio, $\frac{I}{LS}$, at the corresponding energy (or rigidity), the isotopic composition of the primary radiation can give the isotopic composition of the source (or sources) region.

For the study of the chemical composition and the energy spectrum at low energies, it is necessary that the detector be exposed under a minimum amount of residual atmosphere; first, because any significant amount of air will stop the low energy particles and secondly, the fragmentation parameters for heavy nuclei with air are not known very well at low energies and it is desirable to keep as small as possible any errors introduced by the extrapolation of the flux to the top of the atmosphere.

Recently, a number of investigations^{14,15,16,17,18} have been carried

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- 14 F. Foster and A. Debeneditti, Nuovo Cimento 27, 102 (1962)
15 H. Aizu, Y. Fujimoto, S. Hasegawa, M. Koshiha, I. Mito, J. Nishimura, and K. Yokoi, Suppl. Prog. Theo. Phys. 16, 55(1960)
16 M. Koshiha, E. Lohrmann, H. Aizu, and E. Tamai, Phys. Rev. 131, 2692 (1963)
17 V. K. Balasubrahmanyam and F. B. McDonald, J. Geophys. Research, 69, 3289 (1964)
18 W. K. Webber and J. Ormes, Proc. Jaipur Conference (1963)
-

out to determine the chemical composition at low energies. Attempts are also being made to carry out such experiments with satellite borne equipment.¹⁹ In the present experiment, an attempt has been

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- 19 H. Yagoda and K. Fukui, Proc. Jaipur Conference (1963)
-

made to study the charge spectrum of low energy cosmic ray particles with the help of a pure emulsion stack flown from Fort Churchill, Canada on 4 August 1962 under 4.2 g/cm^2 of residual atmosphere. Using the known fragmentation parameters¹⁵ the flux of heavy nuclei has been extrapolated to the top of the atmosphere using the one dimensional diffusion equation.²⁰ The results are compared with

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- 20 M. F. Kaplon and J. H. Noon, and G. W. Racette, Phys. Rev. 96, 1408 (1954)
-

those of other workers and the implications of the results are discussed.

2. Experimental Details

A Emulsion Stack and Flight Details

The emulsion stack consisted of 112 Ilford G-5 and 36 Ilford K-2 emulsions placed after every two G-5 emulsions. There were 19 Kodak NTB4 emulsions kept at one end of the stack. This stack has previously been used to determine the isotopic composition of helium nuclei.^{12,21} The Ilford emulsions were 20 cm x 25 cm x 0.06cm

21 P. J. Lavakare, Thesis, University of Rochester (1963)

and the Kodak 20 cm x 25 cm x 0.0625 cm. The stack was launched in a fiberglass gondola from Fort Churchill, Manitoba, Canada (geomagnetic latitude $\lambda = 70.5^\circ\text{N}$) on 4 August 1962. The cut-off rigidity there according to Quenby and Wenk²² is 0.186 GV. The

22 J. J. Quenby and G. J. Wenk, Phil Mag. 7, 1457 (1962)

plane of the emulsion was kept horizontal until it reached the ceiling, when it was rotated through 90° to make the 20 cm side vertical. The balloon floated under 4.2 g/cm^2 of residual atmosphere for 13 hours and 52 minutes maintaining an almost constant latitude. The packing material, which was of low density, constituted another 0.5 g/cm^2 . The flight curve is shown in Fig. 1.

The stack was processed by the wet hot-stage method; each batch being processed separately. On development of the emulsions it was found that there existed in K-2 emulsions a gradient of grain density in going from the air to the glass surface of the emulsion in addition to a plate-to-plate variation. By following a group of relativistic nuclei through the stack, both the depth and plate-to-plate variation of grain density was established. It was found that within 70 to 130μ from the glass surface of the processed emulsion, the grain density was constant in each plate

to within 5%. Consequently, all measurements were restricted to this region of each K-2 emulsion. The plate-to-plate variation in grain density was similarly established. This variation was within 10% of the mean value, except in two K-2 plates. All values of the grain density were, however, normalized to the grain density in one plate. By rigidly adhering to this process of measurement of ionization, we feel that no large errors were introduced in the final assignment of the nuclear charge and hardly any in the number of primary nuclei in each charge group.

B Scanning Procedure and Selection Criteria

A line scan, 10 cm long, was made leaving 5 mm from the top edge of the G-5 emulsion under a total magnification of x315 using the following criteria:

- (i) all tracks must have a projected length per plate ≥ 3 mm,
- (ii) they must have a projected zenith angle $< 45^\circ$, and
- (iii) all tracks must have ionization $> 6 I_{\min}$ (I_{\min} in the G-5 emulsions is 17 grains/100 μ)

All tracks satisfying the above criteria were first followed in the upward direction to establish that they did not arise from an interaction produced in the stack. Those tracks which did not arise from an interaction were followed into the stack until they stopped, interacted, or left the stack.

3. Charge Estimation of the Heavy Primary Nuclei

The ionization loss for a particle of charge Ze in passing through a medium of charge $Z'e$ and mass number A' is given by the Bethe-Block formula²³

$$-\frac{dE}{dx} = \frac{2C}{\beta^2} \frac{m_e c^2}{\beta^2} Z^2 \left[\ln \frac{4m_e^2 \beta^4 c^4}{(1-\beta^2)^2 I^2 (z')} - 2\beta^2 \right] \quad (1)$$

23 B. Rossi, High Energy Particles, Prentice-Hall, Inc., p 24, 1952

where $-\frac{dE}{dx}$ is the ionization loss per g/cm² of the medium and $I(Z)$ its effective ionization potential. It is clear from Eqn.(1) that whereas a single measurement of the ionization loss is sufficient for the charge determination at relativistic velocities, two measurements--the ionization loss and the velocity, β , are required at sub-relativistic velocities to determine the charge of the incoming particle; this causes considerably more error in the estimation of the nuclear charge. Only recently has it been possible to determine the charge at low energies fairly accurately, both using nuclear emulsions¹⁷ and a combination of Cerenkov-Scintillator counters.¹⁸ Depending on whether a particle stopped in emulsion, interacted, or left the stack, a different method of charge identification was adopted; these are discussed below.

A. Charge Determination of Particles Interacting in the Stack

The fragmentation parameters, that is the number of secondary nuclei produced, on the average, per interacting primary particle, are available at both low and high energies for emulsion as the target medium.^{15,24} The results of the measurements indicate

24 C. J. Waddington, Prog. Nucl. Phys. 8, 1 (1960)

that, on the average, one will have about one α -particle and two singly-charged particles (protons, deuterons, or tritons) produced in an interaction of heavy primary nuclei ($Z \geq 3$). The measurement of the grain density or mean gap length of a non-relativistic singly or doubly charged particle can be directly related to its velocity; since in the fragmentation of heavy nuclei, the velocity of the fragmentation products is equal to that of the primary nucleus²⁵, such a measurement yields the

25 M. F. Kaplon, B. Peters, H. L. Reynolds, and D. M. Ritson, Phys. Rev. 85, 295 (1952)

velocity of the primary. This measurement then provides us with the energy per nucleon of the incoming particles at the point of interaction. In the present experiment the velocity and hence the energy per nucleon of each interacting heavy nuclei was measured by grain counting at least two singly-charged fragmentation products, or by grain-counting doubly charged fragmentation α -particles.

By comparing the grain count of the fragmentation products of interactions occurring in G-5 emulsions with the grain density of showers of high-energy particles in the same plate, the effect of fluctuations in the development was eliminated. Since about one-third of the interactions occurred in K-2 emulsion, it was decided to carry out grain density measurements on α -particles in that plate itself, instead of following them to the next G-5 emulsion. For the few cases in which there were no α -particle products in the fragmentation, a scattering measurement was carried out on the primary. This was done to insure that equivalent grain density measurements are carried out as near the point of interaction as possible. This, we felt, was necessary to avoid the ionization loss which would become important for low energy particles which have a large projected length. Only when we were sure from the nature of the interaction that the incoming particle was relativistic were the interaction products followed to the next G-5 emulsion and grain density measurements carried out there.

In a method of energy determination such as this, it is imperative that an accurate relationship between ionization loss and energy per nucleon be established from relativistic energies down to about 100 Mev/n. This curve was established for α -particles as follows. For the energy range of 90 to 345 Mev/n, well-identified $^{21}\text{He}^4$ nuclei which stopped in the stack were selected for this purpose.

Grain density measurements were carried out in both G-5 and K-2 emulsions at various residual ranges; a total of 25 and 45 measurements were carried out in K-2 and G-5 emulsion respectively. The energy of the He^4 nuclei was calculated from the known Range-Energy²⁶ relation in G-5 emulsion. It was also assumed that the

26 M. Rich and R. Madey, UCRL-2301 (1954)

same relation holds for K-2 emulsions as well, down to very low velocities. This assumption is supported by the measurements of range and energy carried out in emulsions of various sensitivities and for a variety of nuclei down to a velocity of about 1 Mev/n.²⁷

27 H. H. Heckman, B. L. Perkins, W. G. Simon, F. M. Smith, and W. H. Barkas, Phys. Rev. 117, 544 (1960)

In addition, we obtained two break-up events ($N_h = 0$) of α -particles. These decomposed into two singly charged particles. The energy of these α -particles was obtained by coulomb scattering measurements using the coordinate method of scattering²⁸ on a Korstika R-4

28 P. H. Fowler, Phil. Mag. 41, 169 (1950)

microscope. A cell-length of 200μ was employed and the mean \bar{D} value ($4\bar{D}$ replacement was used) was corrected for the stage and reading noise of the microscope. The energy was calculated from the corrected \bar{D} value using the appropriate scattering constant. These calibration events are indicated in Fig. 2 by error bars. The proton calibration was established up to 105 Mev by using stopped protons in a manner similar to α -particles. The plateau value was determined from shower particles and the intervening

region was interpolated using the α -particle calibration as a guide.⁺

In accepting tracks of nuclei which interacted in either G-5 or K-2 emulsion we imposed an additional number of acceptance criteria besides those already mentioned in the selection criteria (Sec. 2 B). These were: (i) the primary nuclei should traverse at least one cm. before the point of interaction, and (ii) the interaction products should be at least one cm. away from a processed edge. The first of these was imposed to insure that there are enough δ -rays or grains available for good statistics on the measurement of the primary and to eliminate any possible edge-effects on grain density or δ -ray density. It was necessary to impose the second restriction because of our method of energy determination. Grain density measurements on tracks of singly or doubly charged particles would certainly suffer if these tracks are very close to the processed edge. We have in the present analysis accepted all ($N_h \geq 0$) interactions satisfying the above given criteria. In spite of the fact that for interaction of S-nuclei with $N_h \geq 8$, we may slightly underestimate the primary energy¹⁶, we have used all interactions with $N_h \geq 0$ for want of better statistics.

In the present experiment, about one-third of the total interactions occurred in the K-2 emulsion. Because of the low sensitivity of these emulsions it was not possible to see singly charged particles. Even for many doubly charged particles, the interaction took place at depths which did not provide the proper region for grain counting in these emulsions. For such interactions an area near the expected position of interaction products was scanned in G-5 emulsion to pick up connected singly or doubly charged particle. Ionization measurements were carried out in

+ The plateau value for relativistic α -particles is less than 4 times the plateau for relativistic protons; this is due to saturation effects in the emulsion response. A similar effect thus occurs for higher Z nuclei.

the secondaries in G-5 emulsion to determine the energy of the incoming particle. Whenever two such fragmentation products were not available, coulomb scattering measurements were carried out to determine the energy of the incoming primary particle.

The tracks of nuclei which interacted in the stack and satisfied the criteria given above were accepted for analysis. For all those events in which the primary track passed through a K-2 emulsion and the ionization was not too large to interfere in accurate grain counting measurements, grain density measurements were carried out in K-2 emulsion. About 400 grains were counted on each track. For all other nuclei, short δ -ray density measurements were carried out in G-5 emulsions. All δ -rays with three or more grains (kinetic energy ≥ 15 Kev) were counted. A standard track of carbon nuclei was always counted before starting any δ -ray density measurements. Fig. 3a and 3b give respectively a plot of grain density in K-2 emulsion/ 100μ versus energy per nucleon and δ -ray density in G-5 emulsion/ 100μ versus energy per nucleon. The energy was determined as explained earlier. The charge and energy assignments were made with the help of a number of break-up events obtained in the stack. A list of these events is given in Table I. We have given the value of the primary energy in Gev/n as measured by the co-ordinate method of scattering as well as by grain density measurement on α -particles of the break-up events. There appears to be a good agreement between the two measurements. Two ionization measurements were made on each primary track: (i) a grain density measurement on each track in the first K-2 emulsion available before the point of interaction and (ii) a δ -ray density measurement in the first available G-5 emulsion before the interaction. Using the α -particle calibration curve as the guide, we have drawn the calibration curves for Beryllium, Carbon, Oxygen, and Flourine. The calibration curve for Lithium was calculated

with the help of the α -particle curve, assuming a Z^2 dependence. These were used for the assignment of the final charge and energy of the incoming particle; though this is certainly an overestimate (Footnote, p. 9), no change in the assignment of nuclei for Li for the L group is influenced by this choice.

B Charge Determination of Particles Stopping in the Stack

A large number of nuclei which have energies less than 700 Mev/n will stop in the stack. For these nuclei we imposed an additional selection criteria besides those already given in Section 2 B. We required that the potential range of the particle must be at least one cm. This was done to insure that we have a statistically meaningful number of δ -rays in G-5 emulsion or a sufficient number of grains in the proper region of K-2 emulsion. For all stopping nuclei which passed through the K-2 emulsion, grain density measurements were carried out in the proper region. A plot of the grain density/100 μ against the residual range is shown in Fig. 4a. The residual range was not corrected for the effect of electron capture at the end of the range, because even for iron nuclei this effect is small¹⁵ ($\lesssim 200\mu$). Fig. 4b shows a plot of $N/100\mu$ against residual range. With the help of the calibration curves given in Table I and that of the similarity law for range-energy relations, we obtained the calibration curves for stopping nuclei. These were used in assigning the final charge values. The residual range was then a measure of the energy of the incident particle.

The selection criteria that we have employed introduces, however, a bias in the acceptance energy criteria. In Fig. 5 we display the effect of our experimental environment on the energy criteria. It is a plot of the cut-off energy at the top of the atmosphere in Mev/n against nuclear charge; specifically the effect of ionization loss in the residual atmosphere packing material and the one cm. of emulsion above the scan line has been folded into

the requirement that the particle have a range one cm. from the scan line. We have accepted in the present work for the final analysis all tracks of nuclei which have energy greater than 200 Mev/n at the top of the atmosphere. It is clear from Fig. 5 that there is a certain bias against low energy M and H-group nuclei. For example, whereas we accept all Be nuclei of energy greater than 180 Mev/n, Nitrogen nuclei of energy ≥ 200 Mev/n and Silicon nuclei of energy ≥ 250 Mev/n only are accepted. We had therefore to correct for this artificial disappearance of low energy M and H-group nuclei. One can correct for this bias under either of the two assumptions of similarity of rigidity spectrum for all nuclei or similarity of the energy spectra for all nuclei (these do not in fact differ greatly since $A \approx 2Z$ for most of the nuclei). We have, in the present analysis, assumed that the energy spectra of the M and H group nuclei are the same as that of the unbiased energy spectrum of the L-group nuclei observed in this experiment and applied a correction for the loss due to this bias.

C. Charge Estimation for Particles Leaving the Stack

Besides the tracks of nuclei which interacted or stopped in emulsion, some tracks of nuclei traversed through the stack. For these tracks, two ionization measurements were carried out; one in the first available K-2 emulsion from the side they entered the stack and the other in the last available K-2 emulsion before the tracks left the stack. These were designated as g_{in} and g_{out} respectively. For tracks of nuclei which were too heavy for reliable grain density measurements or for tracks of nuclei which passed through only one K-2 emulsion, δ -ray density measurements were made in G-5 emulsions at the point of entrance and that of exit. The δ -ray density per 100μ was designated as $N_{\delta}^{in} / 100\mu$ and $N_{\delta}^{out} / 100\mu$ respectively. Using the curves in Fig. 4a or 4b, according as grain density or δ -ray density measurements were

carried out, the corresponding residual range in cm. was computed. We computed R_{in} , the residual range corresponding to the grain density g_{in} or N_{in}^{in} and R_{out} (or N_{out}^{out}). We thus had essentially two ionization measurements at two different residual ranges; g_{in} at R_{in} and g_{out} at $R_{in} + L$ where L is the path length traversed by the nuclei from the point where the first ionization measurement was made to the point where the last ionization measurement was made on the same track. The calibration curve given in Fig. 4a and 4b were used in assigning final charge values. The corresponding energy was determined by the grain density (or δ -ray density) versus energy/n plot of Fig 3a (or 3b). g_{in} was used for this purpose.

In assigning the final charge values, nuclei which gave charge more than 0.5 units and \leq one unit of charge greater than a given charge Z were assigned a charge of $Z+1$ unit. We observed 8 Boron nuclei of energy ≤ 700 Mev/n and 6 carbon in the same energy range.

4. Results

A. A total of 485 tracks were obtained which satisfied the given selection criteria. Using the methods of charge identification discussed in Section 4, we have obtained 39 L-group nuclei and 89 S-group nuclei in the energy range of 200-700 Mev/n; the corresponding number for energies greater than 700 Mev/n being 48 and 209 respectively. Table II gives the distribution of the individual L nuclei, the L and S groups in various energy intervals. Figure 5 gives the energy spectrum of the L- and S- group nuclei. Both are uncorrected for scanning inefficiency and the bias due to the acceptance criterion. The energy interval refers to those at the top of the atmosphere. Table III gives the numbers after the correction for scanning inefficiency (See Appendix A) and for the effect due to bias resulting from the stated acceptance criteria

in Section 2B.⁺ Table IV gives the flux values at the top of the atmosphere in particles/m²Sec. Sr.

Extrapolation to the top of the earth's atmosphere

B The flux values of various groups of nuclei or their ratios, that are of interest from the astrophysical or the origin point of view, are the values of these quantities at the top of the atmosphere. Since all measurements are made under a certain amount of atmosphere, the observed values of various quantities at the flight altitude have to be extrapolated to the top of the atmosphere. Two possible methods have been mentioned in the literature.^{20,29} In the first method due to Kaplon et al.²⁰

29 M. V. K. Appa Rao, S. Biswas, R. R. Daniel, K. A. Neelakantan and B. Peters, Phys. Rev. 110, 751 (1958)

one studies the diffusion of a beam of monochromatic primary nuclei through the atmosphere. One sets up a diffusion equation relating the observed flux at, say x g/cm² of atmospheric air, to the flux at the top of the earth's atmosphere, through the fragmentation parameters of primary nuclei with air nuclei, their interaction and absorption mean free paths. The method calls for an accurate determination of these parameter. The second method²⁹ is based on

+ The ascent correction, i.e. the number of particles recorded in emulsion before the stack was flipped, has been calculated using the flight curve (Fig.1). It is found to be $\sim 1.4\%$ of the flux at the top of the atmosphere. It has not been applied, since it is much less than the statistical error. Moreover, since the stack was flipped, these tracks would not be accepted in the scanning criterion itself.

the fact that primary nuclei arriving at different zenith angles have traversed effectively different amounts of atmospheric. One then sets up a growth curve, which when extrapolated to zero atmospheric depth gives the flux values at the top of the atmosphere. However, this procedure is not suited for a vertical goemetary stack such as the one employed in the present experiment and cannot assess ionization loss effects. We have therefore employed the diffusion extrapolation procedure, using the fragmentation parameters observed in air-like medium^{16,30,31} to obtain the flux

30 G. D. Badhwar, N. Durgaprasad, and B. Vijaylakshmi, Proc. Jaipur Conference (1963)

31 M. W. Friedlander, K. A. Neelakantan, S. Tokunaga, G. R. Stevenson, and C. J. Waddington, Phil. Mag. 8, 1691 (1963)

values at the top of the earth's atmosphere. We have divided the energy region ≥ 200 Mev/n into two groups; (i) the energy interval at 200 to 700 Mev/n and (ii) energies > 700 Mev/n.

The solution of the diffusion equation which takes into account the ionization loss of heavy nuclei in air and the energy dependence of fragmentation parameters cannot be written in a compact form. The extrapolation procedure then requires a rather elaborate numerical integration. However, such a procedure does not enhance the accuracy of the results, for one does not, as yet, know the energy dependence of the fragmentation parameters. We have, as already mentioned, divided the whole energy interval into two groups, 200-700 Mev/n and > 700 Mev/n. These energies refer to the energies at the top of the atmosphere and this partly takes care of the ionization loss. Moreover, in extrapolating we implicitly assumed that the fragmentation parameters are insensative to the

energy down to the incoming primary energy of 200 Mev/n. Since, as already mentioned in Section 3B, we have corrected for the disappearance of primary particles because of the bias introduced by the selection criteria (under the assumption of similar spectra) for all groups of nuclei, the results so obtained would be almost free from any corrections due to the ionization loss. In spite of this, we have used two sets of fragmentation parameters, one for the energy range of 200-700 Mev/n as obtained by Aizu et al.¹⁶ from a study of interaction with $N_h \leq 7$ of heavy nuclei of energy less than one Gev/n in emulsion; for energy > 700 Mev/n a mean value of parameters obtained by Freidlander et al.³¹ and Badhwar et al.³⁰ has been used. The results are presented in Tables IV and V, along with the measurements of other workers. These values do not include the errors inherent in the fragmentation parameters.

This vertical cut-off energy at Fort Churchill²² is 186 GV/n. We have in the present experiment observed a total of eleven nuclei which have energies below this value when extrapolated to the top of the atmosphere. This is consistent with observations that the cut-off is not completely sharp.

Discussion

A number of investigations have been carried out to determine the relative abundance of various charge groups in the primary cosmic radiations. However, relatively few investigations exist in which a good charge resolution has been obtained between the various groups of nuclei and which have been conducted under a relatively small amount of residual atmosphere ($\sim 5 \text{ g/cm}^2$) which makes the correction due to extrapolation relatively unimportant. A comparison of our value of $\int LS(0)$ with those of Koshiba et al.¹⁶ and Aizu et al.¹⁵ shows that there is a good agreement between the various measurements at both low and high energies.

All three emulsion measurements indicate that the value of $\int LS(0)$ between 200-700 Mev/n is greater than $\int LS(0)$ for primary energies > 700 Mev/n. Table VI gives a comparison of $\int LS(x)$ obtained by Balasubrahmanyam and McDonald¹⁷ using a Cerenkov-Scintillator Counter combination and that obtained in the present work. The table shows that whereas our value of $\int LS(x)$ is higher between 400-800 Mev/n as compared to the value for energies > 800 Mev/n, Balasubrahmanyam and McDonald¹⁷ obtained the same results at the two energies, though they are consistent within the stated errors.

We had in the same stack a measurement of the relative intensities of He^3/He carried out between 160-370 Mev/n. The results indicate a value of 0.20 ± 0.05 . Assuming that He^3 nuclei are absent in the source region, Lavakare²¹ has calculated that this corresponds to a traversal of 7 ± 2 g/cm² of interstellar hydrogen. Using the growth curve calculated by Badhwar et al.³²

32 G. D. Badhwar, R. R. Daniel, and B. Vijaylakshmi, Prog. Theo. Phys. 28, 607 (1962)

for high energy particles, our value of $\int LS(0)$ indicates a value of 4.5 ± 0.7 g/cm². Our results, along with those of Aizu et al.¹⁵ and Koshiba et al.¹⁶, and the measurements of He^3 in the present stack, support the conclusion that low energy particles have indeed traversed about twice as much matter as higher energy particles ($\sim 2.5 \pm 0.5$ g/cm²), contrary to the conclusion one would infer from the results of Ref.17. Measurements of He^3/He by Foster and Mulvey⁸ and of $\int LS$ by Foster and Debenediti¹⁴ in a similar stack tend to support the conclusions drawn above.

In the light of the evidence presented, we conclude that low energy cosmic ray nuclei traverse more matter than the high energy nuclei. This observation can be explained in a number of manners;

for example, the source trapping mechanism of Kaplon and Skadron³ or the ionization loss mechanism of Appa Rao³³ may be operative.

33 M. V. K. Appa Rao, Nuovo Cimento, in print (1964)

However, a Fermi type accelerating mechanism³⁴ in the galaxy would

34 E. Fermi, Phys. Rev., 75 1169 (1949)

require the ratios of Γ_{LS} to go in a direction opposite to that observed and hence is not likely to be operative.

Acknowledgment

It is indeed a pleasure to thank Mrs. V. Miller, Mrs. L. Upelincis, Mrs. L. Hawrylak, Mrs. K. Bansal, Mrs. A. Izaks, and Mrs. I. Wolansky for patiently doing the tedious task of scanning. Our special thanks are to Mrs. L. Upelincis and Mrs. L. Hawrylak for making some of the measurements. One of us (S. N. D.) wishes to thank the Danforth Foundation, Missouri, Washington for the financial assistance which made his stay possible here. The help of Mr. William Veeder in preparing the figures is duely acknowledged.

TABLE 1.

List of Break-up Events

No.	Type of Break-up	N_h	Energy in Bev/n of the primary particle at the point of interaction	Grain density/100 μ of the primary particle in K-2 emulsion	γ -ray density/100 μ of the primary particle in G-5 emulsion
1	He \rightarrow 2p	0	0.446 $+0.129$ -0.084	15.1 \pm 1.2	-----
2	He \rightarrow 2p	0	1.63 $+0.40$ -0.21	11.5 \pm 1.2	-----
* 3	Be \rightarrow 2 α	0	0.345 $+0.012$ -0.035	49.1 \pm 1.0	2.84 \pm 0.25
4	Be \rightarrow 2 α	1	0.600 $+0.10$ -0.06 0.401	40.0 \pm 2.0	1.61 \pm 0.10
5	Be \rightarrow 2 α	0	1.55 $+0.45$ -0.20	32.9 \pm 1.5	1.21 \pm 0.10
6	B \rightarrow 2 α + p	1	5.67 $+0.8$ -1.2	37.6 \pm 1.7	1.56 \pm 0.14
* 7	B \rightarrow 2 α + p	1	0.485 $+0.053$ -0.032 0.470	56.5 \pm 2.5	2.74 \pm 0.25
* 8	C \rightarrow 3 α	0	0.872 $+0.09$ -0.11 0.74	47.4 \pm 2.5	3.1 \pm 0.18

No.	Type of Break-up	N_h	Energy in Bev/n of the primary particle at the point of interaction	Grain density/100 μ of the primary particle in K-2 emulsion	δ -ray density/100 μ of the primary particle in G-5 emulsion
9	C \rightarrow 3 α	0	1.50 +0.40 -0.22	48.6 \pm 1.4	2.47 \pm 0.20
10	C \rightarrow 3 α	1	2.0 +0.25 -0.40	48.0 \pm 2.2	2.51 \pm 0.22
11	C \rightarrow 3 α	0	2.30 +0.28 -0.50	50.1 \pm 1.7	2.50 \pm 0.22
12	C \rightarrow 3 α	0	1.43 +0.37 -0.28	-----	5.3 \pm 0.30
*13	0 \rightarrow Li + 2 α +p	0	0.640 +0.14 -0.11 0.66	69.0 \pm 3.0	5.3 \pm 0.30
14	0 \rightarrow 3 α + 2p	0	2.0 +0.24 -0.40	-----	4.04 \pm 0.18
15	F \rightarrow Be + 2 α +p	0	0.571 +0.12 -0.091 0.570	79.1 \pm 2.7	7.42 \pm 0.28

* These interactions occurred in K-2 emulsions. The product particles were followed to the next G-5 emulsion. An area, depending upon the opening angle of the interaction, was scanned in G-5 emulsion to look for any singly charged particle not seen in the K-2 emulsion.

Table II

Observed number of tracks of various nuclei uncorrected
for scanning inefficiency and bias.

NUCLEI ENERGY IN MeV/w	Li	Be	B	L	S
200-300	4	3	2	9	6
300-400	3	2	6	11	28
400-500	2	2	3	7	15
500-600	1	2	4	7	25
600-700	1	2	2	5	15
200-700	11	11	17	39	89
>700	12	13	23	48	209
>200	23	24	40	87	298

Table III .

Number of nuclei corrected for scanning inefficiency & bias.

<i>Group of nuclei Energy in Mev/n</i>	L	S
200-300	10.0	6.4
300-400	11.1	29.8
400-500	7.78	15.95
500-600	7.78	26.6
600-700	5.55	15.95
200-700	43.3	94.6
>700	53.3	222.1
>200	96.5	316.7

Table IV

Flux values at the top of the atmosphere in particles/m² Sec. Sr.

		Energy Interval in Mev/n :		
		200-700	>700	>200
Present work	L	1.65 ± 0.265	1.73 ± 0.24	3.44 ± 0.37
	S	4.00 ± 0.42	9.33 ± 0.65	13.3 ± 0.77
Koshiha et al	L	1.22 ± 0.13	1.91 ± 0.17	3.13 ± 0.22
	S	3.34 ± 0.22	8.78 ± 0.36	12.12 ± 0.43

Table V

Comparison of Γ_{LS} at the top of the atmosphere.

	Energy Internal in Mev/n	
	200-700	> 700
Present work	0.41 ± 0.08	0.19 ± 0.03
Koshiha et al 17	0.38 ± 0.05	0.23 ± 0.023
Aizu et al 16	0.298 ± 0.57	-

Table VI

Comparison of Γ_{LS} at the flight altitude.

	$\Gamma_{LS} (x)$	
	400-800 Mev/n	>800 Mev/n
Present work*	0.384 ± 0.089	0.224 ± 0.036
Balasubrahmanyam & McDonald†	0.304 ± 0.07	0.304 ± 0.07

* $x = 5.6 \text{ g/cm}^2$ of residual atmosphere

† $x = 5.0 \text{ g/cm}^2$ of residual atmosphere

Table VII
Scanning efficiency in %

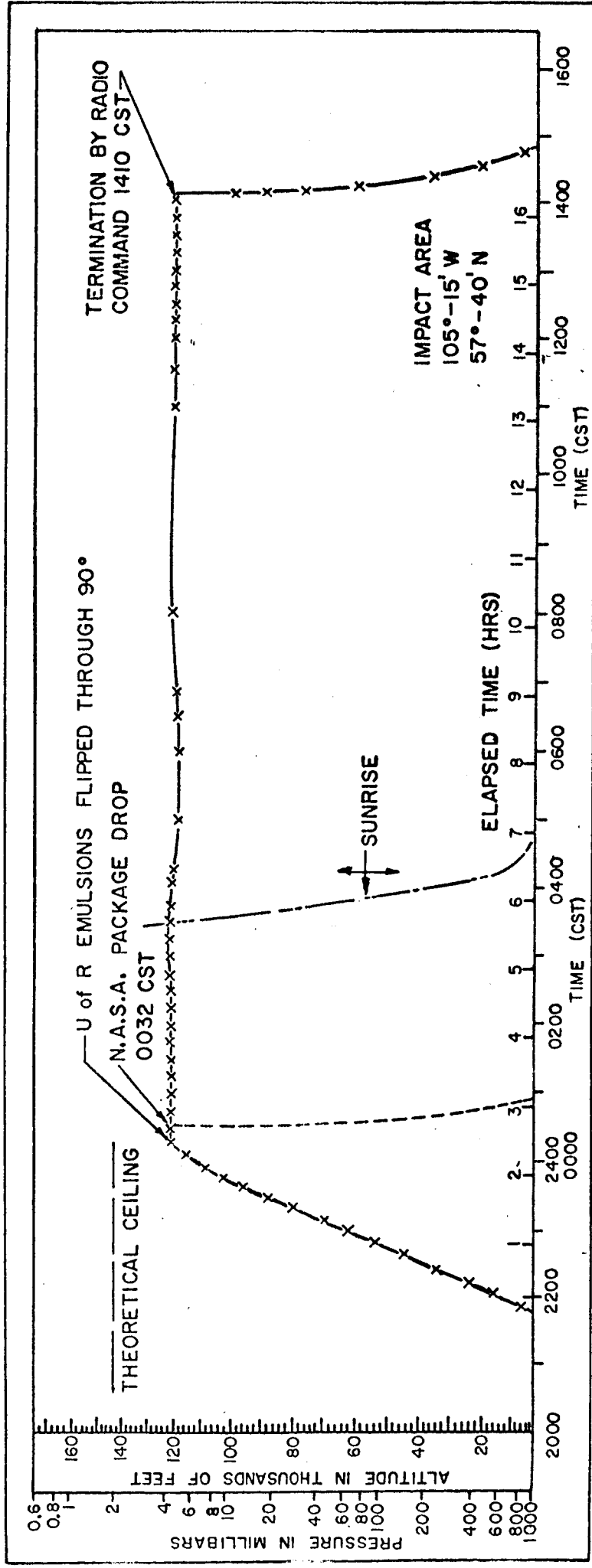
<i>Group of Nuclei Observer</i>	L	S
A	88.4	93.0
B	91.0	95.4
C	90.6	97.0
D	89.7	92.0

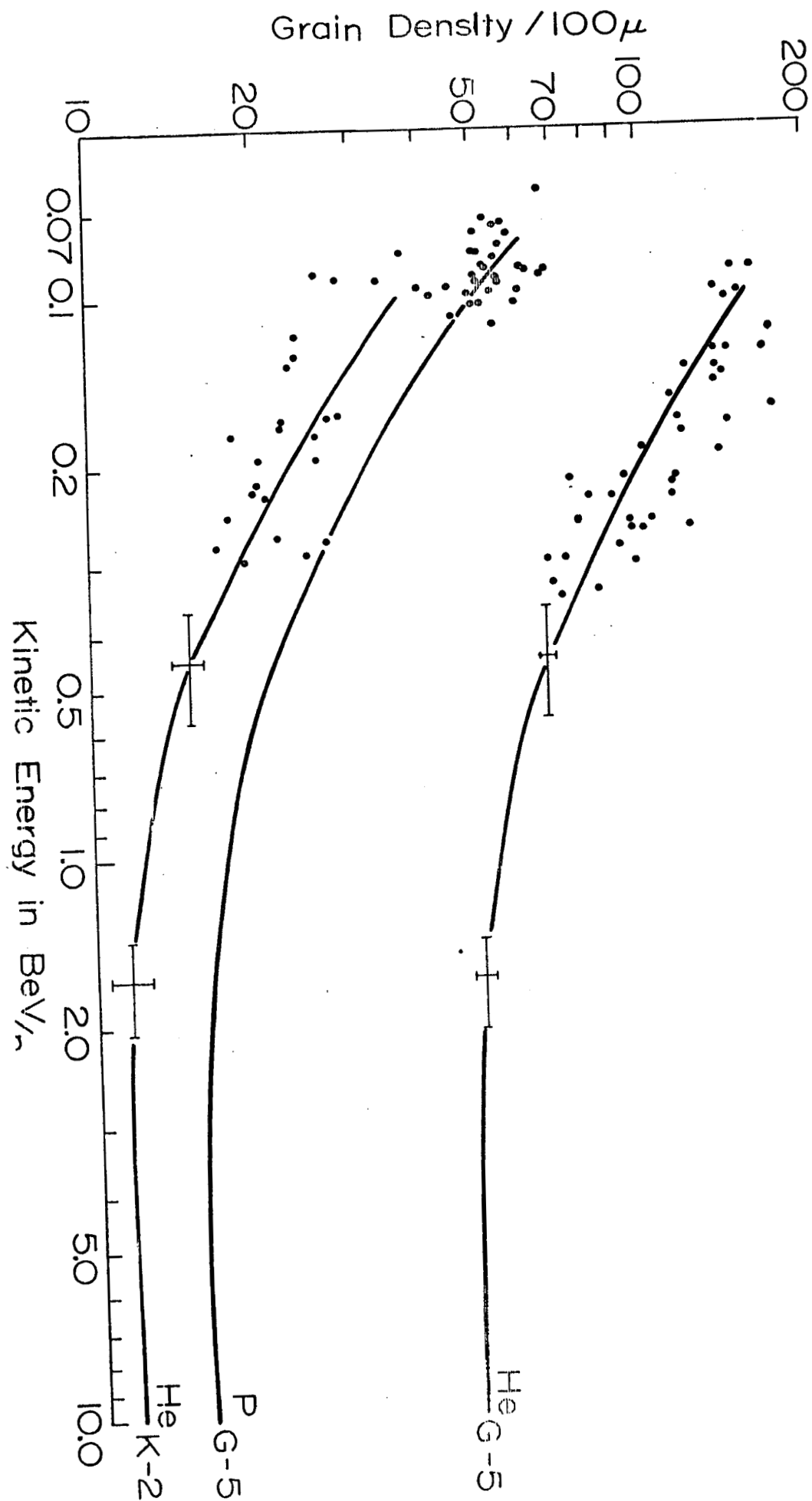
Captions for Figures

- Fig. 1. The flight curve of the Fort Churchill stack.
- Fig. 2. The proton and α -particle calibration curves in G-5 and K-2 emulsions. The dots indicate the measurements on well-identified protons and Helium⁴ nuclei stopping in the stack. The points with error bars are the results of measurement on two α -particle break-up events.
- Fig. 3a A plot of normalized grain density/100 μ in K-2 emulsion versus kinetic energy in GeV/n at the point of interaction for tracks of nuclei interacting in the stack. The Helium calibration curve is taken from Fig. 2. The Lithium calibration curve was calculated from the Helium curve assuming a Z^2 dependence of ionization loss. The other calibration curves are from the break-up events given in Table I.
- Fig. 3b A plot of normalized δ -ray density/100 μ in G-5 emulsion versus kinetic energy in GeV/n at the point of interaction. The calibration curves were obtained from measurements on break-up events given in Table I.
- Fig. 4a A plot of normalized grain density/100 μ in K-2 emulsion versus residual range. The calibration curves are calculated from the known Range-Energy relations in emulsion and the break-up events given in Table I.
- Fig. 4b A plot of δ -ray density/100 μ versus residual range in emulsion. The calibration curves are calculated from the known Range-Energy relations and break-up events given in Table I.
- Fig. 5. A plot of effective cut-off energy in MeV/n at the top of atmosphere as a function of nuclear charge Ze .

Fig. 6

Energy spectrum of L- and S-group nuclei, uncorrected for the scanning inefficiency and bias due to selection criteria at the flight altitude. The energy refers to the energy of various nuclei at the top of the atmosphere.





Grain Density/ 100μ in K-2 Emulsion

